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A review of the mechanism by which EBW detonators function

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Abstract

An introduction to exploding bridge wire EBW detonators is given followed by an extensive critical review of open source literature pertaining to these devices. The aim is to better establish the mechanism of operation. Some authors state that the key mechanism is shock-to-detonation (SDT) while others maintain it is deflagration-to-detonation (DDT), or a complex combination of both. Many authors fail to specifically explain what they mean by these often misappropriated terms.

In addition to EBW detonators, arc detonators and direct optical initiation detonators are also reviewed and it is demonstrated that in this manner the usually coupled effects from both shock and deflagration can be separated. As a result, it is hypothesized that the mechanism of operation in all three detonators is in fact the same: the formation of a plasma with a power of ≈1 MW that, coupled with chemical energy thereby rapidly released by the explosive, drives an abbreviated DDT process.

Finally, several additional experiments are described that if performed will assist the assessment of this hypothesis.

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1 Introduction

1.1 The Detonator

The exploding bridge-wire (EBW) detonator was invented in Los Alamos towards the end of the Second World War [1]. The aim was to create a safe detonator with highly repeatable functioning time ($< 1\mu$s) coupled to a powerful explosive output booster.

This was achieved by discharging a high voltage capacitor across a short, very fine, gold wire to create an air shock, gold plasma and arc next to a pellet of low-density PETN [1]. The exploding of the wire, also called bridge-burst, was discovered to reproducibly detonate the low-density PETN by some mechanism and, by coupling this low-pressure detonation output to a higher density booster pellet, a reliable, highly reproducible detonator was made containing only secondary explosives. A cutaway drawing of a typical EBW detonator is shown in figure 1. The low-density explosive material

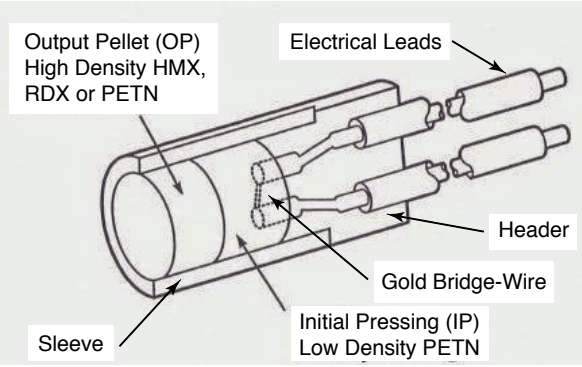

Figure 1: A cutaway drawing of a typical EBW detonator showing the fine gold wire, the low-density initial pressing (IP) and the powerful high-density output pellet (OP).

is commonly called the initial pressing (IP) and the higher density booster material, the output pellet (OP). Initially, the IP was exclusively made from medium to extremely high surface area (SA) PETN (4,000-12,000 cm^2/g), but as time has passed it was discovered that other secondary explosives (e.g., RDX, HMX) could be substituted so long as the powder morphology and surface area were adequately large and the capacitor, cabling and bridge

[1] Approximately 50% of theoretical maximum density, TMD.

were appropriately sized [1]. As intuition would suggest, less sensitive explosives (e.g., RDX and HMX) require larger diameter bridge-wires and greater electrical current than more sensitive PETN for reliable operation.

Studies have shown that contrary to intuition, generally lower SA (coarser) PETN is optimal for lower energy to be required for a specific bridge-wire length and diameter (3000-5000 cm^2/g). However, higher SA PETN accelerates to full detonation more quickly after burst. Hence, to assist temporal accuracy in output time after bridge-burst, a higher surface area PETN is usually used despite requiring slightly more electrical energy for reliable detonation (5000-12000 cm^2/g) [2, 3].

To the knowledge of the author, no one has made a practical EBW from the explosives HNS or NONA although they are excellent choices for exploding foil initiated (EFI) detonator (also known as a slapper detonator) technology where the function mechanism is prompt shock-to-detonation (SDT) in higher density pressed material [1]. The possible significance of this will be discussed later.

Bridges made from gold are by far the most common, but other materials such as aluminum, copper, silver, iron, platinum and tungsten have all been used successfully. The most efficient EBW wire materials have low boiling points, low heats of vaporization and a high increase in resistance at burst [4]. Therefore, in order of efficiency, gold was found to be best, followed by silver, copper, aluminum, platinum, tungsten and finally iron [5, 6]. This list does not consider the effects of corrosion during long term storage, and thus in practical applications precious metals are generally preferred unless special care is taken to ensure that the explosive powder is free from residual acid or other contamination likely to produce slow reactions with the very fine wires. It was discovered that the length and diameter of the wires needed to be optimized for the different metals in PETN IP for greatest operational efficiency [5].

It is remarkable now 75 years later and after literally millions of EBW detonators have been fired, there is still uncertainly about how they actually work. The following key events are generally agreed to occur:

1. Current flow from the charged capacitor heats the bridge conductor to plasma temperature. Initially the resistance of the bridge increases somewhat linearly with temperature, but as melting, vaporization and expansion occurs, the resistance increase becomes highly nonlinear [7].

2. During vaporization and plasma formation of metal from the bridge,

a series of shock waves are produced that couple to the low-density explosive powder. An initial weak shock is observed during vaporization followed by a stronger shock as plasma is made. Given the short timescales, distances and the complex physics, it is possible that these two observed shocks are a result of the shock collection of a number of smaller amplitude shocks [8, 9].

3. Subsequently, an arc is formed in some or all of the conductor plasma, the air, the IP and the IP reaction products. The resistance of this arc is significantly lower than the conductor at bridge-burst.

4. By some action of the bridge-bursting, a building reaction wave occurs in the IP. At some time later, a steady detonation is formed that consumes the rest of the IP.

5. The output shock from the IP detonates the OP by a prompt SDT process.

The uncertainty in function mechanisms occurs in item 4. If the current though the bridge, and voltage across it, are measured, the change in bridge resistance at burst and the inherent inductance of the electrical circuit create a clear signal corresponding to the moment of bridge-burst. That is, at burst the current is seen to plateau or even drop slightly while the voltage spikes as the circuit inductance acts to keep constant current in the increasing resistance of the bridge.

Thus, in detonators used in the laboratory, the onset of bridge-burst can be clearly identified [2]. Additionally the velocity of detonation (VOD) in the IP can be measured (it is approximately 5.0 km s^{-1} for PETN at a density of 0.88 g/cc [10]) as well as for the OP. Therefore, by measuring the time from bridge-burst until the detonation arrives at the free face of the OP an overall function time can be established. Further, if the time steady-state detonation in both the IP and OP should have taken is calculated from the known geometry, any excess time can be identified. That is, if the function time is greater than the steady-state detonation time then another process must have occurred in between.

[2]Identifying the burst time in real-world deployment with longer cables is more challenging since ring-up effects in the cable and the greater inductance mask the current plateau and generally the voltage across the bridge is not easily measured.

When this calculation is performed for real EBWs it is always found that the reaction build-up after bridge-burst until the onset of steady-state detonation indeed takes a significant period of time. That is, the mechanism of initiation of EBW detonators is absolutely not prompt SDT from the bridge-burst, but it could be delayed SDT.

This build-up time is called variously in the literature the 'excess transit time', 'lost time', or 'missing time'. In this paper I shall term the time after bridge-burst until the onset of steady detonation the 'excess transit time' or ETT.

The ETT is found to be a function of capacitor voltage. As the charge voltage is increased, the ETT is found to asymptote to a steady value greater than zero [11]. This asymptotic firing region is termed a hard-fire and is essential if the maximum temporal reproducibility in detonators is required for a specific application. As the voltage is decreased, the ETT is found to increase until a statistical go/no-go threshold is reached. The minimum voltage where reproducible detonation occurs is termed the all-fire voltage while the voltage where 50% of the detonators fire is termed the threshold voltage. The voltage range below the hard-fire voltage down to the all-fire voltage is termed the soft-fire range and can be used safely only if suboptimal timing is acceptable and the effects of cable lengths etc. are carefully accounted for.

For most normally fired detonators, the excess time is 0.7-1.3 μs corresponding to a run-to-detonation distance of $\approx$1 mm. These small time scales and distances contribute to the difficulty of studying these processes. One important caveat is required: the ETT measured this way will also include any run-to-detonation distance from the IP to the OP. Therefore, if the detonation pressure from the IP is not adequate to cause effectively instantaneous SDT transition in the OP, then the excess time metric will falsely ascribe too much time to the build-up phase in the IP rather than some resulting from the junction of the IP and OP.

For example, the RISI RP-80 detonator has a 40 mil (1.02 mm) long, 1.5 mil (38 μm) diameter gold bridge-wire welded to the electrical terminals. The 80 mg IP is 4.98mm long with a density of 0.88 g/cc. This couples to a 123 mg 3.91 mm long output pellet of PBX 9407 (94% RDX). As discussed, the VOD in the PETN is 5 km s^{-1}, the VOD for PBX 9407 is 7.91 km s^{-1} [12]. Using the LLNL computation chemistry code, Cheetah, the estimate for the steady-state detonation pressure in the IP is calculated as 5.5 GPa. The calculated VOD is 4.9 km s^{-1} and this is in good agreement with the experimentally observed VOD value. With no ETT, this requires a function

time of 1.49 μs. The manufacturer's hard-fire asymptotic function time is 2.65 μs. This results in an ETT of 1.16 μs for the RP-80 under hard-fire conditions.

The RISI RP-1 has a very similar construction to the RP-80 except that the gold bridge is soldered to the contacts and the length of the IP (6.38 mm) and OP (5.0 mm) are slightly different. Additionally, the RP-80 has lower specific surface area PETN to reduce the required bridge-burst current slightly ($\approx$3000 cm^2/g), while the RP-1, RP-2 and RP-3 range have higher specific surface area PETN for greater timing reproducibility ($\approx$5800 cm^2/g) [13]. The ETT for the RP-1 asymptotes to 0.7 μs even at burst currents of 2000 A [14]. Because of its significance, it is restated that even under the hardest fire situations possible, prompt SDT is never observed in EBWs.

Returning to the RP-80 again and consulting the run-to-detonation data (Pop-plot) for PBX 9407 suggest a steady-state detonation occurs in less than 0.5 mm at this pressure [15]. Given the uncertainly in Pop-plots at very small runs-to-detonation, this can be considered as prompt SDT [3]. Thus, for this particular detonator, the PETN IP is well matched to the output pellet and extra ETT is unlikely to occur at the interface of the IP and OP. This is also the case for the RP-1 which has essentially the same materials.

Typically the IP is pressed to 0.83-1.0 g/cc. The greater density reduces the sensitivity of the detonator and therefore requires a greater current at burst in the bridge [3]; however, some high specific surface areas PETN materials have pour densities of almost 0.5 g/cc. As a result it is sometimes chosen to press the IP to $\approx$1.0 g/cc so that the powder is physically compressed to a moderate degree during manufacture. The alternative may result in uneven IP density during construction or even partial collapse of the IP during storage and handling leading to very unreliable detonator function. The approximate pour density of $\approx$3000 cm^2/g surface area PETN is 0.3 g/cc while $\approx$6000 cm^2/g is 0.4 g/cc [13].

Although this review mainly relates to EBW detonators, a closely related variant, the arc detonator (AD), will also be reviewed [16, 17]. The AD typically has a very similar construction to an EBW except that there is no conductor between the terminals. To reduce the arc breakdown voltage required to make the AD function, the terminals are ofter closer than in an EBW, 10-20 mil (0.25-0.5 mm), although some EBWs also have bridges this

[3]The reaction zone length in the composition is of order 0.15 mm.

short. Additionally, it is advantageous for the terminals to protrude slightly (≈0.5 mm) into the IP so that the effects of thermal cycling of the detonator are less severe[4]. As with the EBW detonator, PETN is often used as the IP. ADs are fired in a similar manner to EBWs except the charge voltage is often slightly higher. It is found that the energy to fire the detonators is lower than with a comparable EBW [17, 18] and that excellent temporal reproducibility is possible.

The reasons ADs are not more common is three-fold: firstly, they present a quality assurance problem during manufacture and testing because in an EBW the resistance of the bridge can be measured and unusually high or low examples discarded. In an AD, the lead-to-lead resistance is expected to be gigaohms; however, it is not possible to easily tell if this is owing to the gap at the header, or a gap elsewhere in the terminals that may prevent correct operation. Secondly, the energy required to detonate the device becomes uncomfortably close to the energy that can be released by static discharge (ESD), not so much from humans who can store too little under normal circumstances, but from larger equipment that might have much larger capacitance and lower series resistance [16, 18]. As such, ADs are considered too dangerous for many purposes. It would be interesting to revisit this issue by using a less sensitive explosive fill such as RDX or HMX. Lastly, the required peak currents in the leading part of the arc are considerable (450-700 A), as are the peak powers (0.3-1.8 MW). This requires a low inductance fire set and short cabling. This requirement is easily met nowadays, but was challenging in the late 1960s and early 1970s. Additionally, the required proximity of the capacitive discharge unit (CDU) to the AD results in its possible destruction if the main explosive charge is of any significant mass. This may, or may not, be a consideration depending on the application.

Two other detonator technologies that should be reviewed are 'slapper' detonators and direct optical initiation (DOI) detonators. A slapper detonator is so termed because a very high-velocity solid flyer disc of some material interacts with a pellet of pressed explosive[5], and the shock ('slap') from this flyer directly detonates the explosive pellet. The flyer is most commonly launched from an electrically-exploded foil (often called a EFI, exploding foil initiator) [1].

[4]It is presumed that the thermal cycling caused the PETN to contract away from the header producing less coupling from the arc. Raising the terminals appears to help with this phenomenon.

[5]The pellet density is typically 1.5-1.6 g/cc, which is higher than for a EBW detonator.

The EFI detonator is similar to the design of a EBW in that a thin foil is exploded by the discharge of a high voltage capacitor; however, the energy from the exploding conductive foil (often copper) drives a thin plastic disc (often Kapton) situated on top at 2-5 km s^{-1}. It is the shock from the polymer disc hitting the explosive that causes the detonator to function. To effectively drive the flyer, a rate of current rise of 10^3-10^4 A μs^{-1} is required. This is an order of magnitude, or more, greater than that required for the functioning of EBW. To achieve this, an ultra low inductance CDU is required and only short flat transmission lines can be employed from the CDU to the EFI detonator. The impedance of the transmission line is of the order of 1 Ω and so the initial current from a 2000 V CDU is approximately 2000 A. This produces a sufficiently violent foil explosion that the polymer is accelerated in a few hundred microns of flight to the required velocity for prompt detonation to occur in the acceptor explosive pellet. EFIs are seldom used for large run-of-the-mill experiments because the expensive fire set and cable are destroyed by a charge of any significant mass.

Less commonly, a flyer with similar velocity to the EFI design is launched by the interaction of a high-power pulsed-laser on a thin ablative target (usually metallic, ceramic or a combination of both). This very rapid ablation pushes off a thin intact flyer of material (aluminum, aluminum oxide etc.) across a small gap into the acceptor pellet of explosive. Although the mechanism of launch and the material choices are different, the functioning of this detonator design is very similar to the EFI detonator. This type of detonator is now generically referred to as a optically initiated detonator although that term is not actually fully descriptive.

Before the more highly developed laser flyer detonator was optimized, a competing method of optical initiation was tried where a high-power laser pulse interacted directly with the explosive pellet to produce a detonation [19, 20]. This was termed direct optical initiation (DOI). It fell out of favor because it was discovered that the process could be made more efficient by either having the laser absorb onto a thin layer of material between the laser source and the explosive to create an enhanced plasma, or ablating a flyer as described previously. Nevertheless, this arcane technology is of interest because it is a pure optically initiated detonator where no shock is initially generated and the photon energy directly produces chemical reaction.

There is much debate about how detonation is produced in EBWs. Three broad hypotheses exist: 1) it is SDT process with a short run-to-detonation as a result of the shocks from the bridge-burst and arc; 2) it is a DDT

(deflagration-to-detonation transition) [21] event as a result of the thermal input from the wire burst process; or 3) a complex mix of both, with SDT playing a bigger role at higher burst currents and DDT at lower ones. True DDT detonators using PETN can certainly be made, but do require larger physical dimensions for the reaction to build [22].

The key problem is separating the hypotheses because typically the controlled variable in a CDU/EBW combination is the charge voltage. Usually, increasing the voltage increases the bridge current at burst, the power at burst and the energy available post-burst. As such, the voltage simultaneously affects the bridge-burst shock pressure and the arc energy and the power. It is therefore very difficult to decouple the shock input from the thermal one.

1.2 Firesets and Cabling

Practically, all EBW detonators are fired from capacitative discharge units (CDUs). Figure 2 shows the lumped circuit equivalent (inductor, capacitor, resistance, LCR). A high voltage capacitor is charged to specific voltage and a low-inductance fast switch closed to fire the detonator. The circuit will have some parasitic inductance inherent to all elements within it. Generally this inductance is minimized to ensure a rapid rise in current through the bridge (10^2-10^3 A μs^{-1}). However, as previously described, some inductance is beneficial to the operation of EBWs to prevent current being starved at the time of bridge-burst. This is particularly true if two or more detonators are placed in series. Additionally, the circuit will have a parasitic resistance that is generally minimized by design. A typical gold bridge-wire has an ambient resistance of 30-50 mΩ. The parasitic resistance is generally much greater

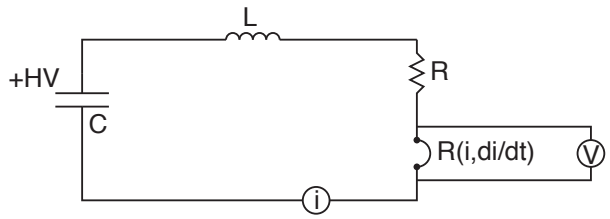

Figure 2: A lumped component representation of a CDU. Also shown is the bridge resistance that is a function of i and di/dt and the key measurement positions.

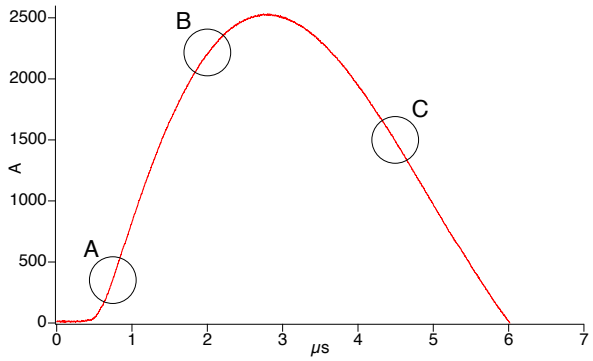

Figure 3: A typical current trace for a CDU discharge. Region A is the bridge-burst zone for a very conservative CDU. Region B represents the zone for an optimized CDU. Region C represents the zone for backside operation of a CDU.

than this (100-300 mΩ), but generally not enough to prevent ringing if the bridge is replaced by a dead-short at the output of the CDU. That is, because the response is under-damped, an undesirable voltage reversal occurs at the capacitor that may shorten its usable lifespan. However, with the addition of a real EBW detonator, or a fixed 250 mΩ dummy load, a damped response is usually observed. As explained earlier, the bridge resistance is a function of current flow history and the resistance can reach ohms before the low resistance arc is established after burst.

With the damped LCR response, the circuit can be sized to fire an EBW in a number of ways. This is illustrated in figure 3. A conservative design (oversized) aims to have bridge-burst at 10-30% of the peak current established afterwards. This is termed front-side burst because the bridge-burst occurs while the current is still building. Historically, for general use, LANL design 'rules-of-thumb' recommended a CDU with 1 μF of capacitance per detonator charged to 2000-2400 V and a peak power at burst of >1 MW for >100 ns (corresponding to >100 mJ) [23]. As high voltage technology has improved, the recommended charge voltage has increased to 3500 V. With standard circuit layout and high-quality components, a CDU with this conservatism may safely be used by non-specialist users with essentially any model of PETN detonator at the end of long coaxial firing cables (50-100 m). For more controlled situations, considerably smaller fire sets can be made where burst occurs at up to 90% of the peak current, but still pro-

vide a hard-fire condition. However, any plans to use this CDU with other configurations requires analysis by a knowledgeable person if the chance of detonation failure is to be avoided.

In exceptional situations, CDUs have been used to fire on the backside of the current waveform. That is, the current waveform is decaying at the time of bridge-burst and there is very little remaining stored energy in the CDU. This almost inevitably results in a soft-fire situation and needs expert review if adequate performance is to be assured. The advantage of such CDUs is that exceptionally small fire sets and low charging voltage can be used when correctly matched to a specific detonator and cable arrangement.

An analytic solution to the lumped LCR circuit model of a CDU is given in [24]. The highly non-linear response of the gold bridge is challenging to model. For an example [25] gives a good explanation of the several physical processes occurring during rapid heating.

In an effort to simplify the analysis of the bridge-burst process, a concept of the 'action-integral' was introduced [26, 27, 28, 29, 11]. It was noticed that for the charged coaxial-cable fire set used for basic research on detonators [26], the instant of bridge-burst, t_b, over a wide range of constant currents, could be calculated from a single number, G, that depended only on the bridge material and wire diameter using the equation,

$$G = \int_0^{t_b} i^2 dt = gA^2, \tag{1}$$

where i is the current, t the time, g a bridge material-dependent constant and A, the bridge-wire area.

Although this simplification is attractive, later experiments with CDU fire sets have shown that the 'action-integral' is not in fact constant [30, 31], although this well-known fact in the detonator community has not been widely mentioned in the literature. At this time it is unclear if it was the use of a charged-coaxial fire set, or something else, that originally led to this incorrectincorrect, or at least over simplistic, conclusion.

An important aspect of the real world use of EBW detonators is the cabling used between the CDU and the bridge. In some situations this cable may only be 0.5 m long, in others it may be 100 m. Whatever cable is used, it must have a voltage rating at least twice that of the expected CDU charge voltage since at bridge-burst it is not uncommon for the inductance to generate that magnitude of voltage increase.

Additionally, the inductance and impedance of the cable is important. Twin core 'zip-cord', also known as 'bell-wire', is the worst possible choice. It will work acceptably over only very short lengths, because, although it is cheap, any loops created by routing add considerable inductance. It has a typical impedance of ≈100 Ω [11]. Thus when a CDU charged to 3000 V is discharged into zip-cord, the initial current reaching the bridge is only 3000/100=30 A. It therefore takes multiple reflections in the cable for the current to 'ring-up' to a value great enough to ensure detonator function at burst (≈200 A). The ring-up time is clearly a function of cable length; therefore, this type of cable must be very short.

High voltage coaxial cable is a better choice. At LANL we commonly use 'C' cable[6], a 20 kV rated cable with an unusually low impedance of 31 Ω [11]. In this case, for a 3000 V charged CDU, the first current magnitude at the bridge is 3000/31=97 A. Another advantage is that owing to the electromagnetic properties of a coaxial cable, loops left when spooling or routing the cable do not add inductance to the transmission line. Originally 'C' cable had dark brown outer insulation; now as a safety feature it is colored red to help distinguish it from other cables used around firing sites.

The choice of high voltage connectors is also important. Clearly the voltage rating is important, but consideration must also be given to safety. The worst possible choice would be the generic BNC connector. Not only is the connector not continuously rated for voltages above 600 V, but it is also commonly used for low voltage diagnostics. Thus, it becomes too easy to accidentally plug the powered diagnostics into the detonator or the CDU into the diagnostics. Both scenarios will give unsatisfactory, if not dangerous, results. At LANL, for safety reasons, the choice of CDU connector must be different from every other connector used at the particular firing site.

2 Background Information

Before reviewing the many papers that discuss the mechanism of detonation in EBW detonators, it will be useful to review the mechanism by which detonation is known to occur in other more defined circumstances. It will be necessary to keep the explanations brief and so it is inevitable that certain subtleties will need to be ignored.

[6]http://www.teledynerisi.com

2.1 The DDT Process

The DDT process is very complicated and poorly understood in detail, particularly for low-density powdered explosives and in three-dimensional solid explosive geometries[7]. From the application of some initial thermal stimulus, an exothermic reaction of the explosive begins. If that exothermic energy is greater then the heat loss, then reaction will grow. A flame front propagates, initially by conductive burning, but transitioning to convective burning resulting in greater propagation velocity [21]. In these initial stages, the permeability of the explosive bed and surface area available to the reactions is critical to the rate of pressurization and burn velocity. The velocity of convective burning is sufficient to produce weak shocks (shocklets) that travel away from the burn and create particle velocity in the material ahead. The resulting compaction wave produces a high-density plug that can, in turn, transition to a strong shock front. This occurs both from the 'shocking up' of the trailing weaker waves because the compacted material has a higher shock velocity than the undisturbed material, and also from PdV work resulting from the compaction and accompanying localization of the shock energy into imperfections producing 'hot spots' where very rapid burning occurs [32].

Once the building shock (or amalgamation of weaker shocklets) supported by energy released from behind feeding forward reaches a sufficient magnitude, the localization of energy and associated high temperature in the coalescing hot spots is sufficient to transition the high-velocity burn into a supersonic burn (a detonation). This last phase is known as SDT; thus the full DDT process will culminate with SDT, providing the rate of energy buildup is greater than the rate of losses from insufficient confinement (required to keep the material pressure building) and the material geometric extents (required to give the plug and strongly shocked material something to react within).

The above two paragraphs are a brief summary of textbook one-dimensional DDT. Most of the DDT literature has studied long thin columns of explosive inside thick walled tubes. The one-dimensional simplification of real world three-dimensional explosive charges makes manufacture and instrumentation of the experiments significantly easier. It also suppresses the complexity of cracking processes in high-density explosives as well as the effects of diver-

[7] e.g., EBW detonators. Owing to the short buildup distance to detonation (ca. 1 mm), the lateral and axial extents of the detonator can be considered semi-infinite if DDT is indeed associated with their function.

gent flow. However, in two- and three-dimensions, the role of pressure-driven cracking is significant because it both produces extra surface area for the burn, which accelerates the growth, and also provides pressure relief paths to the charge extents which will retard the DDT process. Additionally, divergent flow processes, i.e., pseudo-spherical growth of a reaction front at small radius, is influenced by the energy sink of having to heat and shock a larger volume of adjacent material than in a one-dimensional situation. If DDT is operating in EBW detonators, a few complicating factors and only two simplifying factors must be considered.

Because the IP in EBW detonators is a low-density powder bed, on the time scales of interest the effects of particle bed cracking can be ignored. Additionally, the explanation described so far assumed a very low power initial heat source resulting at first in conductive burn. The power at burst in an EBW is of order 1 MW and so it may be safely assumed that convective burn occurs upon burst and that the slow effects of conductive burn can be ignored in this case.

The DDT process in psuedo-one-dimensional columns of PETN and several other explosives have been studied both as a function of particle size and density. A convenient summary is reported in [33]. It is found that in fine-powder PETN pressing densities comparable with IP densities, the burn propagation distance up the confining tube prior to detonation breakout (distance-to-detonation) is minimized (50-60% of TMD). That is, both greater and lesser pressing densities have greater distances-to-detonation. This is an interesting observation with respect to the possible role of DDT in EBW detonator function.

Although the data are sparse, the DDT response of varying both particle size and pressing density is more complex. It appears that for each particle size there is a different pressing density that minimizes the distance to detonation. Generally, larger particles ($>$200 μm) require a higher density (65-75% of TMD) than finer powder ($\approx$20 μm) to minimize the distance (45-60% of TMD). It is unclear, owing to the limited studies, if the minimum distance to detonation is similar for all particle sizes, or if larger particles transition at shorter distances at optimal density. Specifically, the data for two different PETN particles sizes exhibit similar minima, while several other explosives exhibit minima that are significantly smaller at greater particle sizes. More research in this area with representative PETN particle sizes would clarify this.

The permeability of a bed decreases with decreasing particle size and

increasing pressing density (at constant particle size). Therefore, the ease of convective burning is accentuated in larger particle size IP explosive and at lower IP densities. This is in accordance with observations regarding the energy required to operate EBW detonators [2, 3]. However, while increased SA of the powder reduces permeability, it also reduces the average void, or pore, size. This could make the pores either more, or less, amenable to the formation of hot spots from pressure driven collapse, an event that can drive both DDT and SDT.

These DDT findings, if all the current uncertainties are considered, are in broad accordance with the literature for PETN EBW detonators. It is observed that the ETT is lower with higher specific surface area PETN detonators for a fixed CDU charge voltage (power at burst). That is, detonation breaks out closer to the bridge with higher SA PETN. However, the CDU voltage required to function is greater than that required to produce slightly delayed detonation in a lower SA PETN pressed to similar density. In other words, coarser PETN is more sensitive than finer, but builds to detonation more slowly and hence exhibits greater statistical variability in timing.

In summary, the DDT process involves a gradual ramping up of pressure in the explosive bed that culminates in a strong shock being formed and subsequent detonation.

2.2 The SDT Process

There are two broad types of SDT. The build-up process to detonation in homogeneous explosives (liquids, very fine pressed powders and solid explosives pressed to extremely close to theoretical maximum density (TMD)) and heterogeneous explosives (most solid cast or pressed explosives) is found to be very different under shock loading [34, 35]. It is widely agreed that heterogeneous explosives build up from shock-to-detonation because of hot spot formation.

It is easy to show that the bulk temperature rise associated with even a strong shock is too low to produce rapid reaction in most explosives of practical interest. Therefore, something must be localizing the shock energy into a much smaller volume that then can reach much higher temperatures (hot spots) and that these start separate but growing reaction sites that coalesce into a single shock front at a formation rate that can support a steady-state detonation [36].

There is considerable debate about all of the imperfections in the explo-

sive that can produce useful hot spots, but they include hydrodynamic pore jetting, adiabatic gas-filled pore collapse, adiabatic shear band formation, viscoplastic work at voids, shock wave interactions at impedance discontinuities, etc. [32]. It is thought that the first listed mechanism, hydrodynamic pore jetting, is the most significant for SDT and steady-state detonation in most pressed explosives because the jet-tip velocity is of comparable velocity to the detonation wave and so provides for the production of hot spots contemporaneous with the detonation front rather than behind it, as with the other mechanisms.

Therefore, a moderate-strength shock acting on a pressed explosive is presumed to create localized burn sites some distance behind the shock by the action of having transited through the imperfect explosive. The burn sites grow and coalesce to release energy that can feed forward towards the shock because the shocked and unreleased explosive is at a higher pressure than the ambient explosive and so has a higher shock speed. This extra energy arriving at the lead shock initially increases its strength and thus propagation velocity, but at some point, the velocity of the shock asymptotically approaches the sound speed in gases behind the detonation front. Energy released behind this sonic locus (later time reactions) can no longer reach the lead shock and so a steady-state supported shock (detonation) results.

The imperfections that can localize enough energy to be useful towards both SDT and DDT have a finite range of sizes (0.1-10 μm [32]). Imperfections that are too small quench, owing to the heat required for expansion being greater than can be provided by the reaction volume. Hot spots that are too large produce energy that arrives too late to practically contribute in real size explosive charges.

For homogeneous explosives, a different shock process occurs. In these explosives there is nothing to localize the shock energy because there are no imperfections of appropriate size[8]. Instead, the passage of a strong shock does raise the bulk temperature of the explosive sufficiently that exothermic energy begins to be released. While the shock continues to run into fresh explosive, a feedback reaction is initiated in the material already shocked where energy from the initial shock produces reaction energy that heats the explosive so that greater reaction occurs, releasing yet more energy. At some

[8]Liquid homogeneous explosives such as nitromethane can be made into heterogeneous explosives by the addition of other ingredients. The mechanism of detonation is observed to alter when this is done [37].

time later (tens of nanoseconds to microseconds depending on the explosive and shock strength), a thermal explosion occurs in the material that was shocked first [34]. The resulting detonation then forms a super-detonation that catches the initial strong shock because the partially reacted material behind the shock is at much higher than ambient pressure and so the shock velocity is greater. Once the super-detonation catches the lead shock, steady-state detonation at a lower velocity occurs after a decay period.

Normally, pressed explosives are considered to be heterogeneous; however, some powders used in IPs are so fine (<1 μm) that the pore size in a collapsed bed may be approaching the lower limit for traditional hot spot theory to operate (<0.1 μm). Hence the response to a strong shock may resemble a homogeneous thermal explosion rather than the more commonly observed heterogeneous mechanism. This will not be the case for coarser particles of the same explosive pressed to low or moderate density.

An example of this phenomenon is found in HNS [38]. Type 1 HNS (5-10 μm particle size, 2,100 cm^2 g^{-1}) is found to behave as a heterogeneous explosive at approximately 92% TMD (1.6 g/cc). Very fine HNS-FP (1-2 μm particle size, 8,000 cm^2 g^{-1}) at the same density behaves as a homogeneous explosive when shocked at low to moderate pressures (3-5 GPa). Presumably, this finer powder, when pressed, deforms to form voids that are too small to form viable hot spots upon shock loading. When strongly shocked, the thermal explosion process is so rapid that the super-detonation is not resolved as it is at lower pressures.

For sustained shocks it is found that, at constant material density, the smaller particles are more sensitive than larger under SDT conditions down to minimum size when the sensitivity decreases again. An investigation of RDX powder at 90% of TMD showed that in order of sensitivity 21 μm powder was more sensitive than 100, 138 and 250 μm, but that 3.9 micron powder was slightly less sensitive than 21 μm [39]. As noted before, this is probably a result of the efficacy of the hot spot forming imperfections being related to the particle size of the pressed powder.

A similar observation, but for slightly different reasons, occurs in short shock loading. In both PETN [40] and HNS [41], it was discovered that laser-driven thin-flyers that promptly detonated small particle size pressings did not detonate larger particle size ones. As noted by the authors, this is a result of the very short shock duration traversing several small particles and voids before pressure release and therefore initiating reaction, while not even traversing a single particle of the larger material and so effectively running

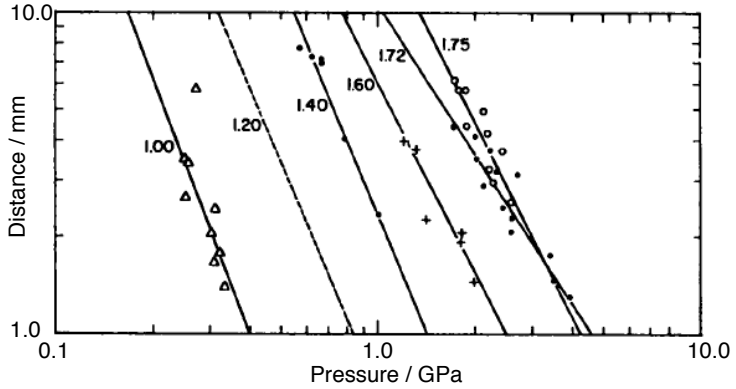

Figure 4: The Pop-plot for PETN as a function of density. Adapted from [42].

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into imperfection-free explosive and producing only modest bulk heading.

An important distinction between SDT and DDT is that detonation produced by SDT involves the passage of a shock, or shocks, from the start of the process. DDT transitions to SDT only at the end of the process. Therefore, observations of the particle velocity from building reactions in explosives can be distinguished because a DDT process will have a slow to fast, or perhaps just fast, ramping particle velocity versus time profile prior to the formation of a shock profile, while SDT will have weaker shock building in strength until a steady-state strong shock is formed. In the case of homogeneous explosives, a strong shock of greater than steady-state magnitude may be transitively observed in the pre-shocked region prior to steady-state detonation. Examples of the particle velocity versus time profiles from the SDT build-up to detonation in heterogeneous and homogeneous explosives can be seen in [37].

3 A Review of Previous EBW Research

3.1 The Role of SDT

The easiest explanation for the functioning of an EBW detonator is direct SDT from the action of the bridge-burst and indeed at least one researcher just states that as fact [14, 11]. There is remarkably little literature on the sustained 1D shock response of low-density PETN. Possibly this is because

the difficulty of manufacturing coherent test charges from this fragile material, the relative difficulty of generating strong shocks in a material with a very low impedance and the short run-to-detonation distances of interest at those pressures make diagnostics with adequate temporal resolution challenging to field.

There appears to only be one Pop-plot curve for PETN at densities relevant to EBW detonators (1 g/cc) [43]; see figure 4. Reference [43] also suggests values for the shock velocity versus particle velocity response of unreacted PETN at that same density (often, but technically incorrectly, called the unreacted equation of state (EOS)). As reported in [42], comparison of this EOS curve with others from higher density PETN leads to a simple variation in offset of the Y-axis intercept with respect to density; see figure 5. That is, the gradient of the curve stays constant while the initial bulk sound speed is a function of density. However, closer observation reveals a problem with that extrapolation to densities below 1 g/cc; the bulk sound speed at 0.9 g/cc would have to be less than zero and this is clearly not physical. Therefore, this simple Y-axis intercept approximation breaks down around PETN densities of interest for EBW detonators, if not before. Nevertheless, from ETT measurements it is known that the run-to-detonation distance corresponds to $\approx$1 mm. Consulting the Pop-plot, a sustained pressure of 0.4 GPa is required for this run distance in PETN at 1 g/cc. This is a very low shock pressure compared with most explosives. However, there is an important caveat to this that is seldom expanded upon in the literature exploring the operation of the EBW. That is, the Pop-plot is only valid for sustained steady shocks. If the initial shock releases before detonation breaks out, the insult is termed 'short-shock' and it is found that the pressure to produce detonation needs to be increased substantially over that required for sustained shocks. Indeed, this is the region in which slapper detonators operate where the very thin flyer fails to support the shock in most practical circumstances and, as a result, for adequate detonator function much higher flyer velocities are required than would be required from a thick flyer of the same impedance [44].

Alternatively, the shock can release from the side or from the shock formation geometry (termed divergent flow). Given that the wire in an EBW is much longer than its diameter, any strong shock produced must be largely cylindrical. In fact, because the wire is located close to the polymer header, a semi-cylindrical outgoing shock is created that is somewhat supported by a complex reflection process from the header surface. The resulting divergent

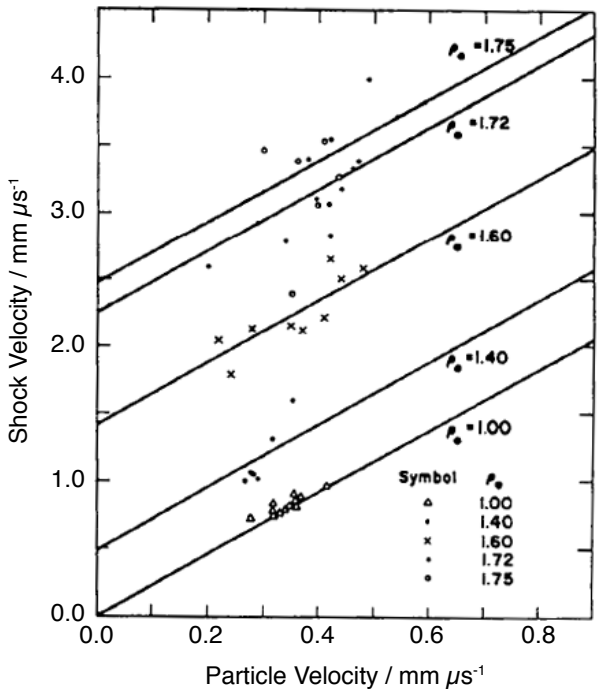

Figure 5: The shock velocity versus particle velocity for PETN as a function of density. Adapted from [42].

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flow at small radius will also destroy the approximation required to use the Pop-plot data directly.

3.2 The Magnitude of a Shock from an EBW

The magnitude of the shock from the EBW has been studied [45, 46, 47]. This is a difficult measurement to make and so generally some from of Schlieren high-speed photography of the shock has been used to estimate the shock pressure from the known properties of the transparent medium (air, water or siloxane rubber) into which the bridge-bursts occur. Earlier studies made use of air and close examination revealed two shocks from an EBW, an initial weak one followed by a second stronger one that catches the first [8, 48]. However, it is known that wires that burst in air have a very different resistance vs electrical current profile compared with wire burst in PETN and this will affect the shock(s) produced.

Measurements in water, or rubber, suffer from the difficulty that, although the density is approximately correct, the impedance of water is much higher than low-density PETN. That is, the bulk sound speed in water and rubber is almost two orders of magnitude greater than that measured for low-density PETN. Because the effective impedance of the EBW 'piston' is not known, the shock-matched pressure into PETN cannot readily be calculated from the value measured in water. Interestingly, only a single shock is typically observed. In water this may be because the second stronger shock overtakes the initial weaker one at very small radius.

Despite this, the peak calculated shock pressure in water from a typical EBW burst varies widely (0.3-1.5 GPa) [49, 45, 50, 47] and is found to have a complex structure of duration ≈100-200 ns [49, 51]. It will be noted that this is of the correct order of magnitude to explain the functioning of an EBW detonator if the huge caveats are ignored regarding the fact that the shock duration is too short to fully support the lead shock until detonation breaks out and that the divergent flow that results at small radii from bridge-burst also greatly complicates things. Also, the waveforms presented in [49] show a marked double shock, perhaps even a ramp, to a second peak. This feature is not reported by others.

Measurements reported in [50] are particularly significant because they measured the output pressure as a function of CDU energy and calculated values between 0.3 & 1.1 GPa. Pressures above 0.5-0.6 GPa corresponded to hard-fire conditions and so the ETT will have ceased to vary much in

real detonators. The Pop-plot for low-density PETN suggests that the run-to-detonation will vary widely between those pressure values. This is not observed. The ETT for different detonators varies greatly and is ≈650 ns for the RP-1 [14], ≈300 ns for the ER-213 [30] and 1.16 μs for the RP-80[9] [51]. Even if the absolute shock pressure measurement value is in error, the over 50% increase in pressure should have had an effect on the ETT in the event that EBW detonator function is a SDT process.

This issue has received little comment regards the asymptotic ETT value [14, 30, 31]. Unless another rate-limiting physical process occurs, it would be expected that larger and larger burst currents produce larger and larger shock pressures. From the Pop-plot it is known that larger shock pressures produce shorter run-to-detonation. In fact since the Pop-plot is always plotted on a Log-Log plot, increased shock pressures produce much shorter run-to-detonation values.

DDT is a build-up process that may not be able to occur above a certain rate. That is, there may be a finite limit to the physical rate of the process. SDT has no such limit observed in other aspects of explosives. A greater magnitude shock always results in faster build up. In extreme cases SDT can be overdriven and an increased VOD results until release processes drop the velocity down to the steady-state value.

The role of divergent flow in SDT is large. It has been shown that the velocity of a metal sphere impacting explosive must be 3 times the velocity of a flat plate of similar dimensions to produce SDT [52]. This is because the spherical geometry releases the equal magnitude initial shock pressure so quickly compared with a pseudo-one-dimensional flyer. The effects of cylindrical shocks (two-dimensional, 2D) have not been studied experimentally, but it is reasonable to expect the release effect to lie between the sphere (3D) and flat plates (1D).

As a result of these caveats (the effect of short-shocks and cylindrical divergence), one might expect the measured shock pressure from an EBW to have to be much greater than the Pop-plot might suggest for SDT to cause the functioning of the detonator. From the experiments conducted so far, this appears not to be the case, although as explained, translating the shock pressures observed in water to porous PETN is not straightforward.

[9] As explained earlier, the RP-80 design is optimized for a slightly lower required burst current and fire set robustness, rather than for optimal timing reproducibility.

3.3 Photographic Observations of Detonators

High-speed photography has been used for many years to observe the process of bridge-burst [8, 53, 48]. Most often the bursts were performed in air or in another gas with controlled pressure. It is known that the impedance of the medium surrounding the wire affects the expansion process. This in turn affects the resistance versus time and so affects the burst process itself [7]. Occasionally, bursts were photographed in water in order to radically change the impedance of the material surrounding the bridge [50, 47].

Photographing the build-up to detonation is harder because most explosive powders are white, attenuate visible light and are highly scattering. For this reason, observations are usually performed at the transparent walls of special detonators designed for the purpose [54, 2, 5].

The most extensive study, [2], through very careful optical path design and illumination, observed shock waves propagating in the PETN crystals after burst. The magnitude of these shocks, determined from their velocity, increased as the CDU voltage increased. Further, by observing detonation breakout at the transparent walls, increased CDU voltage resulted in detonation breakout occurring closer to the original bridge location.

Additionally, increased PETN density required increased CDU voltage for the same breakout distance to be observed and increased SA PETN reduced the breakout distance for otherwise the same initial conditions. Finally, it was noticed that close to the threshold voltage, detonation often started off-axis with respect to the bridge location. That is, a randomly located volume somewhere near the original bridge achieved conditions required for detonation to occur and reaction in the rest of the IP propagated from that location.

In summary, photographic observations resolve a shock in the IP bed and detonation breakout occurring some distance away, on-axis for hard-fired detonators, but often off-axis for very soft-fired detonators. It is clear that the detonation in PETN is not homogeneous SDT in nature since breakout does not occur in the material shocked first near the bridge and observation location. However, the mechanisms underway after bridge-burst until detonation breakout could equally well be SDT, DDT or a mixture of both.

Taking X-ray pictures of functioning detonators to observe the interior density variations and therefore infer the mode of operation is challenging for three reasons: a) the X-ray attenuation of low-density organic solids is minimal at higher photon energies and so low energy x-rays are required

(40-60 keV) that are highly attenuated by other elements of the experimental apparatus. b) A temporal resolution of order 10 ns is required to discriminate the changes occurring at bridge-burst. That requires very high-power X-rays to achieve sufficient exposure energy on the recording medium. c) The relevant dimensions of a detonator are a few millimeters in size and so to avoid blurred X-rays, a source with a very small spot size is required. It is only recently that some researchers are beginning to overcome these considerable obstacles and generate new insights.

3.4 Observations of Cut-Back Detonators

The particle velocity of IP beds during detonator function have been measured by cutting back an assembled detonator to a known distance above the bridge [55, 56]. The PETN output surface was placed against a 'silvered' stress-maintaining window. Optical velocimetry was then used to measure the interface particle velocity versus time profile after the bridge-burst. By varying the distance from bridge to window, a pressure build-up history can be measured. In both cases, it was clearly shown that a ramp wave was present initially that transitioned into a steady-state detonation some distance later.

In [55], building pressure ramp waves were observed at 0.655 & 0.914 mm from the bridge, but by 1.181 mm a steady-state detonation had formed. In this detonator the IP was 0.9 g/cc. The bridge geometry is not described, but the author describes the functioning as a hard-fire. In [56], a weak ramp wave is observed at 0.76 mm, a stronger ramp at 1.44 mm and steady-state detonation at 2.5 mm. In this case the IP was 0.93 g/cc. Neither the bridge geometry nor the firing conditions are described. If the function of an EBW is SDT, a ramp wave should not have been observed at any stage, only shocks of varying magnitude. This strongly indicates that the initiation process in a EBW is a DDT process.

A shock wave may initially drive a shock compaction wave, but that will decay to a ramp wave if not supported. The estimates vary for the duration of the shock from an EBW, but are of order 100-200 ns [45, 51]. The ETT is typically several times that and so it is probable that an unsupported shock situation occurs. Forced compaction waves have been shown to bypass the experimentally inconvenient initial stage of the DDT process allowing a more controlled experiment that observes the more interesting latter stages [21]. Thus, the bridge-burst shock could still play a significant role in the

operation of an EBW detonator, but the underlying process would still be DDT.

It has been shown that bridge-wire bursts in both inert powders, and PETN that failed to then detonate, result in approximately hemispherical cavities forming near the bridge location [57]. It is therefore clear that a compaction mechanism, driven by the bridge-burst, is operating at some time scale.

3.5 The Effects of Interstitial Gas

Further evidence of a DDT mechanism rather than an SDT process is provided by [45]. In this research the type of interstitial gas and gas pressure was altered for a nominally-fired fixed-design detonator. It was discovered that the probability of the detonator operating varied tremendously according to the gas fill in the PETN. When argon, a gas that readily ionizes, was used, detonation was assured at almost any fill pressure. When SF6, a gas that is very difficult to ionize, was used, detonation only occurred at very low fill pressures where the Pashen curve suggested ionization was possible at the voltage potentials created in the header. The probability for fills of nitrogen (78% of air), a gas with an ionization threshold that is between argon and SF6, fell between the other gas values.

Previous SDT research has shown that the presence or absence of gas in shocked PETN had no effect on the Pop-plot[10] [43]. This observation, in conjunction with the observation about the role of gas pressure on EBW detonator functioning, further supports the idea of a principally DDT mechanism operating in EBW detonators. Additionally, whatever process operates in nominally fired EBW detonators requires some degree of ionization of the interstitial gas. It is notable that ionization aids the establishment of an arc after bridge-burst. Indeed reference [45] suggests that SDT is not the mechanism by which EBW detonators function, but instead proposes it is a coupling of shock and pre-sensitization of the PETN by the arcing process.

[10]This is additional evidence that while the adiabatic collapse of gas pores may be important in deflagrating explosives or in starting deflagration, it is not a useful source of hot spots at the rates required for SDT.

3.6 Arc Detonators

Examining the function of an arc detonator may be highly important to understanding EBW detonators, for while a shock is associated with the discharge, it is an order of magnitude weaker than the action of bursting a wire [58], thereby removing one of the obstacles discussed previously: that of coupled effects.

In ADs, it was discovered that the energy required for detonation decreased with increasing surface area PETN. That is, the mechanism of initiation was more efficient with higher surface area PETN (10,500 cm^2/g) than lower (3,500 cm^2/g) [17]. It is reported that the stored energy on the CDU needed for self-triggered discharges needed to be 40-90 mJ to assure detonation with an average value of ≈60 mJ. Detonation was observed occasionally at energies as low as 20 mJ under some configurations.

It was also reported that reliable functioning of ADs happened when the majority of the energy discharge occurred in the initial 30 ns of the arc. Equal total energy discharges, where the energy arrived later, more commonly resulted in failure to detonate.

The AD function energy values above are broadly supported in reference [57] for triggered discharges in both EBW and arc detonators. In this research, the threshold energy for arc was measured as 26 mJ and 34 mJ for the normally detonated EBW. The all-fire threshold was 42 mJ for the arc version and 100 mJ for the EBW. However, it should be noted that the activation volume for the arc version was substantially smaller (150 μm spark gap) than the detonators tested in [17] (500 μm spark gap) and, until some unknown lower limit, this may require less energy to initiate detonation.

There were concerns about air pressure and the functioning of the AD, owing to the expectations that an arc formed in the interstitial air would be required initially to detonate the device reliably [17]. However, it was found that the response was more complex than that and the required firing energies were moderate at ambient air pressure, but lower at very low air pressures. At intermediate pressures, failures to detonate occurred. It should be mentioned that this is probably closely related to the fact that the arcs formed as a result of self-breakdown across the terminals. Owing to the limitations at the time, low-inductance switched fire sets could not easily be made and as a result, the efficacy of the AD was closely related to the self-breakdown voltage at the gap. This breakdown voltage was moderate at ambient pressure, low at intermediate pressures and higher at very low pressures (vacuum).

The explanation and model presented in [17] assumes no surface tracking of the PETN crystal since it is often considered a good dielectric and the experimental results are therefore solely explained using the Paschen curve for air. Subsequent research has indicated that ionization of the surface of PETN occurs at high potentials per unit distance [45]; therefore, it is quite possible that ADs can be made to function adequately, even at intermediate air pressures if the fire set is externally triggered after full voltage charging rather than from self-breakdown.

A modified SE-1 detonator (essentially the same design as the RP-1) has been used in arc mode [18] using very high SA PETN (14,000 cm^2 g^{-1}) in the IP. The gap that the arc had to jump was systematically varied; however, the go/no-go threshold was identified as 54 mJ with an all fire threshold of 73 mJ. This is similar to the values found in [17] and [57].

Significantly, it was also discovered that a very low capacitance (3.55 nF), moderate inductance (300 nH) fire set charged to extremely high voltage (13 kV) could detonate the modified SE-1 with an initially intact gold bridge, but without any apparent bridge-burst appearing in the current trace. The total stored energy was approximately 300 mJ in this configuration.

The voltage across the bridge was apparently not measured; however, it is possible that the potential across the terminals was sufficient that an arc was established parallel to the conducting bridge. That is, the potential across the 50 mΩ bridge with accompanying voltage spikes associated with an impedance mismatch at the bridge location may have been sufficient to establish an arc. This would explain this particular mechanism of operation because the CDU clearly contains sufficient energy to operate in arc detonator mode if the arc only needs to last 30 ns.

The effect of melting the bridge-wires in EBW detonators by the application of a low voltage prior to attempting to fire them normally in arc mode has been studied [59]. An electrical current between 2 and 20 A were applied to melt the gold wire. As might be expected, melting at greater current resulted in a larger gap being formed between the wire ends.

In all cases the results of test firing the now damaged AD showed that significantly greater energy was required than to fire the original pristine gold bridged detonator. This is attributed to the wire heating process producing partial reaction in the PETN, including sintering of the remaining powder, and therefore creating a void between the residual wire ends and the PETN. The energy required to fire an AD is lower than a similar bridged detonator and so the required energy for the melted ADs would have been substantially

greater than would be required for a pristine AD of similar design.

3.7 Direct Optical Initiation

Another exception to the problem of coupled effects from increased voltage on an EBW CDU is direct optical initiation of the explosive powder, usually by laser. In this case, the process is essentially shock-less and so purely thermal or photo-chemical in nature. As with the electrical arc created after an EBW bridge-burst, high-power laser pulses are observed to create plasma. Presumably this is from direct interaction with explosive crystals because it occurred even under vacuum [20].

Direct optical ignition was studied in PETN, HMX and HNS [19]. In this research various frequencies of laser were used with a 10 ns pulse at a spot size of 1 mm diameter. An ETT of ≈100-150 ns was noticed in PETN. At a laser wavelength of 1064 nm, a pulse energy of 56 mJ was required for detonation PETN at 0.9 g/cc. This dropped to 40 mJ at 308 nm and 24 mJ at 266 nm. The author suggests that light in the ultra-violet range, below 350 nm, may directly break chemical bonds in molecular crystals such as PETN. It was also noticed that confinement was required for detonation to occur at 1064 nm, but not at the shorter wavelengths. The type of PETN was not reported, but may have been LANL type 12. The HMX could be made to detonate, but required greater pulse energy than for PETN.

A similar study was undertaken by different researchers [20]. They studied PETN, RDX and HNS. The effect of density and particle size of the response of PETN was reported using a 20 ns pulse and a spot size of 0.6 mm diameter. For the finest PETN used at a density of 0.9 g/cc, the threshold energy required at 1064 nm was 20 mJ with hard-firing occurring at 41 mJ. Using slightly coarser LANL type 12 PETN, the energy required for hard-fire increased to 53 mJ.

For a fixed density, the particle size had little effect on ETT. In contrast it was found that the ETT increased with decreased powder density (from 1.4-0.9 g/cc) and the variability in ETT increased as well. It may be significant that the particle size of the fine PETN studied for this segment of the study was abnormally fine (21,000 cm^2/g) and so it is possible that, as discussed elsewhere, the hot spot formation was suppressed under compaction compared with most PETN reported so far. The study also reported that the effect of shorter laser wavelengths on sensitivity was not as dramatic as noted by [19], but also confirmed that confinement was no longer required

for detonation to occur.

By observing the light emission from the window in contact with the PETN, and through which the laser entered, it was noticed that after the initial plasma formed in the PETN, the light intensity dropped to essentially zero for a period before rising again. This was attributed to the arrival of a retonation wave from the detonation starting somewhere in the interior of the pressing. For this reason, the idea of a detonation occurring because of a delayed thermal explosion immediately behind the window (indicative of a homogeneous response) was discounted. They report that the reaction transitioned to detonation between 0.4 and 2.5 mm into the powder bed depending on the conditions.

The addition of carbon to PETN lowered the power required for detonation [60]. This is attributed to reducing the scattering length in the translucent PETN and therefore concentrating the energy into a smaller volume of explosive.

No researchers have observed detonation in HNS at any achievable pulse energy despite reflectometery measurements showing that the energy absorbed at the laser wavelengths will be similar to PETN and HMX. Other researchers have been unable to detonate HNS despite the additions of dopants [60].

Extensive searches have revealed essentially no papers studying DDT in HNS and so its propensity to react violently under pure thermal excitation is unknown. The SDT sensitivity of HNS has been studied extensively, particularly related to its short shock response because of its use in EFI detonators [38, 61]. At comparable density ($\approx$1.6 g/cc) and particle size ($>>1$ μm), HNS is found to be less sensitive than both RDX and HMX under SDT conditions and very much less sensitive than PETN [12].

3.8 The Effect of Post-Bridge-Burst Energy

The effect of post-bridge-burst energy on the functioning of EBW detonators has been studied using modified CDU units with an additional fast-acting triggered current-shunt circuit to quickly remove the current flow from the bridge [62, 51]. The difficulty of this approach is that it is very difficult to cease the bridge current instantly in this manner and so some attenuated current flows for a period after the shunting occurs. This creates a more complex analysis problem.

In [62], the effects on post-burst energy on platinum and gold wires was

studied in PETN. The researcher was clearly focusing on the effects of substantial energy after burst and so very few 'no-go' events were noticed. However, close inspection reveals that with a platinum wire, a 'go' occurred when the post-burst energy was ≈200 mJ and a 'marginal' and a 'no-go' occurred when the post-burst energy was ≈0 mJ. With a gold wire, a 'go' occurred when the post-burst energy was ≈200 mJ and 'no-go' occurred when the post-burst energy was ≈0 mJ. The post-burst energy was calculated from the time where sufficient energy had been delivered to totally vaporize the bridge.

In [51], an RP-80 was studied. Total failure to detonate occurred with a post-burst energy of <30 mJ and ≈50 mJ was required for a hard-fire. It is presumed that bridge-burst was defined in the usual manner; the time at which the peak bridge voltage was measured. In [63], the effect of post-bridge-burst energy on the velocity of the bridge debris and plasma cloud was measured. It is reported that the post-burst energy increased the velocity of the cloud over clouds without post-burst energy. Interestingly, when there was no post-burst energy, the burst was delayed by a short time, but still occurred. This delay is not enough to explain the accompanying change in ETT observed in a functioning detonator under those same lower energy conditions.

In most of the literature on EBW detonators, bridge-burst is assumed to have occurred when the voltage across the bridge is at maximum and a small inflection is observed in the current curve. The obvious role of post-burst energy on correct functioning suggests that although it is a very convenient timing metric for day-to-day discussions of EBWs (because it is easy to quantify), a better metric might be found elsewhere. Indeed [31] suggests that comparison of EBW detonator performance is assisted by considering the energy until peak power, not peak voltage. That is, although the power is the instantaneous value of VI, neither the voltage across the bridge (V), nor the current (I) drops immediately after the voltage spike. As a result of the rapid rate of current rise just prior to burst from most CDUs, the peak power occurs some time shortly after 'voltage-indicated bridge-burst'. It is probable that this new suggested metric is correlated with the required post-burst energy for correct functioning of the detonator discussed previously.

4 Discussion and Conclusions

The mode of functioning in exploding bridge-wire (EBW) detonators is obviously complex. It is clear that they do not operate by prompt shock-to-detonation (SDT) because there is a measurable excess transit time (ETT), even under hard-fire conditions [14]

The fact that the ETT asymptotes to a non-zero time is important for considering traditional SDT with a run distance or run time. Measurements show that the shock produced by a bursting wire increases in strength with increasing voltage on the CDU [50]. In traditional SDT, increased pressure always reduces the run-to-detonation. Observations of cut-back detonators show that they produce ramped compression waves prior to the establishment of a steady-state detonation [55, 56]. Again, this demonstrates that traditional SDT does not occur.

However, it is clear from analysis of inert powder simulated EBW detonators and real PETN detonators that failed to detonate, that the bridge-burst shock does form a compaction wave that moves the initial-pressing (IP) powder away from the bridge location [57]. Energy in the form of PdV work will then heat the powder as well as form a compaction wave, possibly leading to a deflagration-to-detonation (DDT) related high-density plug.

Both the magnitude and duration of the shock from the bridge-burst are at best contested, and at worst, unknown [49, 45, 50, 47]. Without these data it is not possible to assess the applicability of one-dimensional, sustained, shock strength input to run-to-detonation data for PETN (a Pop-plot). Because the EBW bridge produces a pseudo hemi-cylindrical divergent shock, it is unlikely that the sparse Pop-Plot for PETN has much applicability at all. Instead, an energy fluence approach, such as described in [52], and subsequent papers by the same author, is more likely to be successful in predicting response, providing SDT is the ignition mechanism.

Additional evidence favoring a DDT-type function method comes from observations of the essential role that post-bridge-burst energy has on the likelihood of detonation occurring. It has been demonstrated that late time arcing between the EBW electrodes is highly advantageous under normal operating conditions [45]. Further, it has been demonstrated that starving the arc of energies less than 30-200 mJ after burst prevents normal detonator function [62, 51]. Since this energy arrives after the main shock from burst, it will serve to both slightly support the shock, but also provide a high-power thermal flux ($\approx$1 MW).

It is interesting that these magnitudes of the values required for function are also in agreement with the largely empirically developed conservative design 'rules-of-thumb' used at LANL for 50 years. That is, an arc with a >1 MW for >100 ns (corresponding to >100 mJ) is required for reliable EBW detonator operation [23].

Experiments on PETN arc detonators have demonstrated that energies of between 26 & 90 mJ are required for normal functioning and that detonation was most likely if the energy was deposited in less than 30 ns [17, 57]. Because there is no working fluid in an AD compared with a regular EBW detonator, the shock from a comparable energy discharge is weaker in the case of the arc, possibly an order of magnitude [58]. This strongly suggests that the thermal input is more significant than shock input in functioning an AD.

Further evidence pointing to a heating, or at least heat-flux, role in the operation of EBW detonators comes from direct optical ignition (DOI) studies of PETN [19, 20]. Energies of between 20 & 56 mJ were required. Detonation was easier to achieve at laser wavelengths in the ultraviolet, and this was attributed to a likely photochemical effect at wavelengths below approximately 350 nm. Interestingly, the laser pulse durations used were 10-20 ns in duration and the presence or absence of air in the interstitial space between PETN crystals was found to be irrelevant.

Estimates of the temperatures of arcs in air suggest a value of order 10,000 K. By considering the Planck distribution of energy at such temperatures, the peak emission will occur in the soft to hard ultraviolet (400-300 nm).

It is therefore suggested that the functioning of EBW detonators, ADs and DOI detonators are all related to the deposition of a suitable heat flux (20-90 mJ in 10-30 ns) and therefore the formation of a plasma. The plasma can result from a high temperature arc and associated bridge-wire gas, or be formed directly by the action of sufficient photon energy being absorbed by the explosive. High temperature arcs and ultraviolet lasers have the advantage that their photons appear to result in a photochemical effect in the explosives commonly used in EBW detonators (i.e. PETN, RDX, HMX).

The hypothesis is thus that the heat flux and plasma begin the release of additional chemical energy from the explosive. The rapid expansion of the heated zone, and the growing energy release from combustion, form a compaction wave that builds in strength until it shocks up to a magnitude that produces SDT in the remaining IP.

Under this hypothesis, the function is a modified DDT process where the

initial, slow, conductive burning process is bypassed and instead convective burning occurs, driven in part by the shock compaction wave from the bridge, but mostly by the expansion of the plasma and subsequently from the energy released from chemical reaction of the PETN. Owing to the large input power driving the DDT process and the shock-sensitive nature of PETN, the distance-to-detonation can be very small (≈1 mm) compared with traditional 1D DDT columns where a short distance-to-detonation is 10 to 30 times that. It is short even by the standards of optimized PETN-based DDT detonators where the distance to detonation is ≈6 mm under strong confinement.

This hypothesis suggests that the bridge-wire is no more than a fuse to allow the CDU current to build from zero to an arc power where rapid DDT can occur. This has been postulated before [16, 57]. It also implies that the historically significant, and experimentally convenient, bridge-burst, indicated by the inflection in the current rise and the voltage spike, is the beginning of the thermal operation process, rather than the stimulus that directly results in detonation.

Confirming or disproving this hypothesis could be done in many ways. A few suggestions are made here.

The current termination after bridge experiments performed so far are useful, but suffer from the problem that stopping the current instantly in a CDU is extremely hard. Therefore, with that approach a small amount of energy is still deposited after cutoff, creating complexity in analysis. Given the small values of post-burst energy that are proposed to result in normal detonator function, an alternative approach is suggested. The charged coaxial line fire set has been used before; however, in this situation it provides the considerable advantage that once the cable is discharged, the current drops very quickly because there is little inductance and no other stored energy available to support it.

Therefore, if the length of the coaxial cable is altered at a fixed charge voltage, which will be higher than traditional CDU units, two useful experiments can be done. Firstly, the length of the cable can be tuned to cut off current flow very abruptly around the bridge-burst time. In this way a very accurate measurement of the energy required post-burst for normal detonator functioning can be made. Secondly, the same design of detonator can be operated in AD mode by not installing a bridge-wire. Owing to the higher charge voltage in a coaxial fire set, prompt arcing at typical lead spacing (1 mm) can be assured in an IP with previously measured EBW properties. From comparison of the energy required in each case to operate the detonator

at similar ignition volumes, a greater understanding of the roles of the bridge and the arc can be found.

Another experimental variant that may be possible along the same lines is a DOI-augmented electrical detonator. That is, by coupling in a multi-mode optical fiber that sits between the bridge-wire leads, laser energy in the UV could be used to assist the functioning of an electrically operated detonator fired below threshold, either of arc or EBW design. By controlling the additional laser energy supplied (time and power), the requirements for the return to normal detonator operation could be examined.

A good understanding of the role of the bridge, the arc, the plasma and explosive combustion will go a long way towards demonstrating the validity, or otherwise, of the hypothesis presented above.

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